Analysis of Aggregate Exposure to Chlorpyrifos in the NHEXAS-Maryland Investigation

Yaohong Pang,[1] David L. MacIntosh,[1] David E. Camann,[2] and P. Barry Ryan[3]

[1]Department of Environmental Health Science, College of Agricultural and Environmental Sciences, University of Georgia, Athens, Georgia, USA; [2]Department of Analytical and Environmental Chemistry, Southwest Research Institute, San Antonio, Texas, USA; [3]Department of Environmental and Occupational Health, Rollins School of Public Health, Emory University Atlanta, Georgia, USA

As part of the National Human Exposure Assessment Survey (NHEXAS) in Maryland, we collected indoor air, carpet dust, exterior soil, and duplicate diet samples from a stratified random sample of 80 individuals to evaluate aggregate daily exposure, contributions of specific pathways of exposure, and temporal variation in exposure to chlorpyrifos. We collected samples from each participant in up to six equally spaced sampling cycles over a year and analyzed them for chlorpyrifos. We used chlorpyrifos concentrations in each medium and self-reported rates of time spent inside at home, time and frequency of contact with carpet, frequency of contact with soil, and weights of the duplicate diet samples to derive exposure to chlorpyrifos from each medium as well as average daily aggregate exposure (nanograms per day). The mean aggregate daily exposure to chlorpyrifos of 36 measurements obtained from 31 people was 1,390 ng/day (SD, 2,770 ng/day). Exposure from inhalation of indoor air accounted for 84.7% of aggregate daily exposure to chlorpyrifos on average. Chlorpyrifos concentrations in indoor air and carpet dust and the corresponding exposure rates were significantly correlated. Repeated short-term measurements of chlorpyrifos in carpet dust from individual residences were strongly correlated over time (reliability coefficient, $R = 0.90$), whereas the short-term measurements of chlorpyrifos in indoor air ($R = 0.55$) and solid food ($R = 0.03$) had moderate to weak reliability. Exposure to chlorpyrifos through those media and in aggregate based on direct measurements reported in this study can be used to understand better the accuracy of pesticide safety assessments. *Key words*: **aggregate exposure, chlorpyrifos, dust, indoor air, reliability, soil, solid food.** *Environ Health Perspect* **110:235–240 (2002). [Online 5 February 2002]**
http://ehpnet1.niehs.nih.gov/docs/2002/110p235-240pang/abstract.html

Passed into law in 1996, the U.S. Food Quality Protection Act (FQPA) requires a more comprehensive assessment than ever before of pesticide exposure, dose, and effects (*1,2*). In particular, the FQPA directs the U.S. Environmental Protection Agency (EPA) to consider exposure to potentially sensitive subgroups in the population, coincident dietary and nondietary (i.e., aggregate) exposure, and contemporaneous multichemical (i.e., cumulative) exposure for pesticide risk assessment. To implement the FQPA, the U.S. EPA has been developing new methods and models to assess aggregate pesticide exposure that could occur in community settings (*3–5*). Few reports have been published on direct measurements of pesticide exposure from different potential exposure pathways and the aggregate exposure posed by these exposures in residential settings. This information would be valuable for evaluating exposure models and for epidemiologic studies of the relationship between personal pesticide exposure and possible human health effects (*6–9*).

In this paper we report the results of a longitudinal study of aggregate daily exposure to chlorpyrifos, a commonly used organophosphate pesticide, in community and agricultural settings. The data presented are the product of a pilot investigation of temporal variation in human exposure to selected contaminants in multiple media—the National Human Exposure Assessment Survey in Maryland (NHEXAS-MD). The objectives of our study were to assess aggregate daily exposure to chlorpyrifos from indoor air, carpet dust, exterior soil, and food; to identify the predominant pathways of chlorpyrifos exposure among those media; and to evaluate the reliability of a short-term measure of exposure for assessment of long-term average chlorpyrifos exposure.

Methodology

Study population. A stratified probability sample of 80 individuals over 10 years of age selected from four contiguous counties and the city of Baltimore in Maryland enrolled in the study from September 1995 to September 1996. All participants provided informed consent under protocols approved by an institutional review board. Details of the sampling strategy and demographic characteristics of the participants are reported elsewhere (*10*). Briefly, we collected samples from selected environmental and biologic media, as well as questionnaire data, from each participant in as many as six 1-week periods (cycles) approximately equally spaced between September 1995 and September 1996. Cycles 1–6 correspond to 20 September to 23 December 1995, 15 January to 23 February 1996, 27 March to 20 April 1996, 22 April to 15 June 1996, 18 June to 27 July 1996, and 30 July to 18 September 1996, respectively.

Sample collection and analysis. We collected an indoor air sample by using a small pump to draw air through an integrated sampler containing an inertial impactor with a particle cut-point of 10 μm followed by a filter and polyurethane foam (PUF) plug (URG Inc., Chapel Hill, NC). We placed the sampler approximately 1.5 m above floor level in an area of unrestricted air flow in the principal activity room of the household as identified by the study participant. The pump ran at 4 L/min with a programmable timer–controller that directed air through the PUF sampler for 10 min out of each 70-min period during 1 week. Total collection time for each sample was 24 hr, and the target sample volume was 5.76 m^3. Participants completed a questionnaire on daily time budgets and behavior patterns on each day of the 7-day sampling period for a given cycle. We used responses to questions concerning body weight and time spent inside at home to estimate the inhalation rate and average daily time inside at home, respectively, for each participant.

We obtained a house dust sample on the first day of each sampling period by vacuuming the carpet in the activity room of the household using a high-volume small surface sampler (HVS3; CS-3, Inc., Sandpoint, ID) (*11*). By making eight passes with the nozzle over each strip of carpet, we collected house dust > 5 μm in diameter into a precleaned Teflon bottle with size selection effected by a cyclone separator. We sieved out particles > 150 μm in diameter in the laboratory before extraction and analysis of the dust samples. We recorded the area sampled,

Address correspondence to D. MacIntosh, 206 Environmental Health Science Building, University of Georgia, Athens, GA 30602-2102, USA. Telephone: (706) 542-5542. Fax: (706) 542-7472. E-mail: dmac@uga.edu

This research was supported by the U.S. Environmental Protection Agency under cooperative agreement CR822038-1, the U.S. Department of Agriculture Hatch (project GEO00843), and the University of Georgia Research Foundation.

Received 16 May 2001; accepted 20 September 2001.

which had a target value of 2 m^2. Responses to the question, "How much time did you spend laying down or sitting on the carpet or rugs at home today?" gave us the average daily frequency of contact with carpet and average daily time on carpet.

Where possible, we obtained a soil sample from the respondent's residence on the first day of each home visit. We took soil samples from the yard to evaluate potential exposure from bare soil and play areas. If the household had a garden for growing food, then we obtained a sample of garden soil to evaluate this possible food and dermal exposure pathway. We sampled foundation soil to evaluate the potential for exposure from past application of pesticides for termite control or other uses. If we found no areas of the property that met the sampling criteria, we took no samples. We composited aliquots of soil obtained from different locations of the residence into a single sample in the field, and used responses to the question, "Did you have soil or dirt from your yard in contact with the skin today?" to obtain average daily frequency of contact with soil.

Because of limited resources, we selected a portion of the indoor air, carpet dust, and soil samples for analysis. We analyzed approximately 75% of the indoor air and carpet dust samples collected in cycles 1, 3, and 5, and approximately 25% of those sample types collected in cycles 2, 4, and 6. To conserve resources further, we analyzed approximately half as many soil samples as indoor air or carpet dust samples based on the assumption that this outdoor exposure medium was less important and less variable than indoor exposure media in this population. Details of sample selection criteria can be obtained from the authors. We analyzed indoor air, carpet dust, and soil samples for chlorpyrifos and 10 other pesticides at Southwest Research Institute in San Antonio, Texas. Briefly, samples were Soxhlet extracted with 6% ethyl ether in hexane, cleaned through a Florisil column, and analyzed by gas chromatograph/mass spectrometry-selected ion monitoring with a 30 m × 0.25 mm i.d. DB5 column (J & W Scientific, Folsom, CA).

Details of the solid food sample collection, analysis, and diet questionnaire procedures are reported elsewhere (*9,12*). Briefly, we requested participants to prepare a duplicate portion of meals consumed on four consecutive days during each sampling cycle. A field technician recorded the weight of each 4-day solid food sample in cycles 2–6. We homogenized samples (solid food separate from beverages) and analyzed them for selected pesticides at the U.S. Food and Drug Administration laboratory in Kansas City, Missouri. We did not record the weights of duplicate solid samples in cycle 1; hence, we used the average weight of duplicate solid samples on cycles 2–6 for each respondent to estimate the respondent-specific duplicate diet weights in cycle 1.

Quality assurance. To ensure traceability and accuracy of the data, we performed a series of quality assurance steps. A chain-of-custody form followed each sample and questionnaire from the field to the laboratory and finally to the database manager. We omitted from subsequent analysis any sample data point not accompanied by a completed chain of custody. We analyzed field blanks, duplicate field samples, and reagent blanks for the presence of chlorpyrifos as quality control measures of field and laboratory methods. We did not detect chlorpyrifos in any field blank or reagent blank in our study. Chlorpyrifos concentrations were comparable in the pairs of primary and duplicate samples. We determined detection limits (DL) and recovery efficiencies for chlorpyrifos in each medium throughout the study. The average DL was 0.720 ng/m^3 (range, 0.577–0.773 ng/$m^{3)}$ in indoor air samples, 240 ng/g (35.2–1,700 ng/g) in carpet dust samples, and 5.24 ng/g (2.96–9.16 ng/g) in soil samples. The chlorpyrifos DL in food samples was 100 ng/kg and was constant over the course of the study. We determined recovery efficiency by fortified samples. We spiked extraction matrices with known amounts of analyte, which were about 200 ng of chlorpyrifos into PUF and 6 µg of chlorpyrifos into 2.0 g of sieved dust or 30 g of soil, and we spiked solid food samples to a concentration in the range of 10.9–18.6 µg/kg. We analyzed spiked samples as ordinary samples. The spike recoveries centered near 100% and had a range of 95.0–119% for PUF samples, 78.0–152% for dust samples, 92.0–144% for soil samples, and 84.7–95.8% for duplicate solid food samples.

Table 1. Data and models used to estimate exposure to chlorpyrifos.

Parameter	Unit	Reference
Inhalation of indoor air		
C_{air}, concentration of chlorpyrifos in indoor air	ng/m^3	Primary data
T, time indoor at home	min/day	Primary data
Body weight	kg	Primary data
Surface area (body weight × 0.049 m^2/kg)	m^2	(*29*)
IhR, inhalation rate (surface area × 5 L/min/m^2 for male, surface area × 4.7 L/min/m^2 for female)	L/min	(*30*)
AF, absorption factor (constant, 1.0)	NA	(*4,18*)
Exposure (C_{air} × T × IhR × AF/1,000)	ng/day	Calculated
Incidental ingestion of carpet dust		
$C_{dust,}$ concentration of chlorpyrifos in carpet dust	ng/g	Primary data
IgR, ingestion rate (constant, 0.56 mg/day)	mg/day	(*13*)
F, frequency of contacting carpet	times/day	Primary data
AF, absorption factor (constant, 0.5)	NA	(*4,26,27*)
Exposure (C_{dust} × IgR × F × AF /1,000)	ng/day	Calculated
Dermal absorption of carpet dust		
C_{dust}, concentration of chlorpyrifos in carpet dust	ng/g	Primary data
Weight of dust	g	Primary data
Area of carpet	m^2	Primary data
L, loading on carpet (C_{dust} × weight/area)	ng/m^2	Calculated
TF, transfer coefficient (constant, 0.6 m^2/hr)	m^2/hr	(*31*)
T, time on carpet	hr/day	Primary data
AF, absorption factor (constant, 0.01)	NA	(*4,26,27*)
Exposure (L × TF × T × AF)	ng/day	Calculated
Incidental ingestion of soil		
C_{soil}, concentration of chlorpyrifos in soil	ng/g	Primary data
IgR, ingestion rate (constant, 480 mg/day)	mg/day	(*13*)
F, frequency of contacting soil	times/day	Primary data
AF, absorption factor (constant, 0.5)	NA	(*4,26,27*)
Exposure (C_{soil} × IgR × F × AF /1,000)	ng/day	Calculated
Dermal absorption of soil		
C_{soil}, concentration of chlorpyrifos in soil	ng/g	Primary data
AdF, adherence factor[a]	mg soil/cm^2	(*13*)
SA, surface area (constant, 5,000 cm^2)	cm^2	(*13*)
F, frequency of contacting soil	times/day	Primary data
AF, absorption Factor (constant, 0.01)	NA	(*4,26,27*)
Exposure (C_{soil} × AdF × SA × F × AF/1,000)	ng/day	Calculated
Ingestion of solid food		
C_{food}, concentration of chlorpyrifos in solid food	ng/kg	Primary data
W, weight of average daily duplicate plate	kg/day	Primary data
AF, absorption factor (constant, 0.5)	NA	(*4,26,27*)
Exposure (C_{food} × W × AF)	ng/day	Calculated

NA, not applicable.
[a]We estimated the adherence factor as average of the adherence factors among different parts of body associated with relevant outdoor activities, such as greenhouse gardening and irrigation installation.

Data analysis. The models, variables, and constants in the data set used to estimate exposure to chlorpyrifos from each pathway are shown in Table 1. Chlorpyrifos concentrations in each medium below the respective DL were set to zero. We quantified inhalation of indoor air, incidental ingestion of carpet dust, incidental ingestion of soil, dermal absorption of carpet dust, dermal absorption of soil, and ingestion of food as the pathways of exposure to chlorpyrifos. We calculated pathway-specific exposure (nanograms per day) as a function of chlorpyrifos concentration in the exposure medium; time spent in the microenvironment; inhalation, ingestion, or contact rate with the medium of interest; and the fraction of chlorpyrifos absorbed by the lung, skin, and gastrointestinal tract (*13*). We computed aggregate daily exposure to chlorpyrifos as the sum of average daily exposure from all six pathways.

We generated descriptive statistics for chlorpyrifos concentration and exposure from each pathway and in aggregate, samples containing a detectable amount of the analyte. We computed contributions to aggregate exposure from each pathway for each observation. The data exhibited strong positive skewness, and some exposures were the product of binary factors yielding nonnormal distributions (skewness > 3.21). For nonzero pairs of data, we used Spearman correlation to evaluate rank associations between chlorpyrifos concentrations in sample media and exposures from different pathways. We calculated Pearson correlation coefficients for comparison as well.

Reliability is a concept used to describe the degree to which a randomly selected single measure of exposure taken from a set of measures for an individual represents their long-term average exposure. To estimate the reliability of a short-term measure of daily exposure to chlorpyrifos for individuals, we computed the intraclass correlation coefficient of reliability (R) with indoor air, carpet dust, and food concentration data. R is the ratio of between-person variance to the total variance observed in a repeated-measure study (*14*). R ranges from 0 to 1, with values near zero indicating low reliability and values near one indicating high reliability. In this study, the temporal variability observed is a characterization of within-person variability, whereas the total variability is a combination of the temporal variability of within-person and the between-person variability.

Results

The final data set contained 107 observations from 44 participants for indoor air, 126 observations from 50 participants for carpet dust, 60 observations from 41 participants for soil, and 379 observations from 75 participants for solid food. Thirty-six home visits from 31 participants yielded contemporaneous measurements of indoor air, carpet dust, soil, and solid food, and we used these observations to calculate aggregate daily chlorpyrifos exposure. The numbers of observations for each medium of the six sampling cycles are shown in Table 2.

Chlorpyrifos was present at detectable levels in 92.5% of indoor air samples, 79.4% of carpet dust samples, 40% of soil samples, and 38.3% of solid food samples. Table 3 presents summary statistics of chlorpyrifos concentrations in indoor air, carpet dust, soil and solid food samples; exposure to chlorpyrifos from each pathway; and aggregate daily exposure. The mean dust loading from participating households was 3.55 g/m^2 (SD, 8.01 g/m^2) with a range of 0.10–51.97 g/m^2. The distribution of chlorpyrifos concentrations in each medium was skewed right and ranged over two to four orders of magnitude. The fraction of sampling visits for which there was nonzero exposure to chlorpyrifos because of detectable levels of chlorpyrifos in the exposure medium and contact with the exposure medium were as follows: indoor air, 93% (99 of 107); carpet dust, 45% (57 of 126); soil, 18% (11 of 60); and food, 38% (135 of 356). Aggregate daily chlorpyrifos exposure computed as the sum of exposure from the six pathways was also skewed right and ranged from 13.5 ng/day to 12,800 ng/day, with a mean of 1,390 ng/day (SD, 2,770 ng/day).

Exposure from indoor air accounted for the majority of aggregate daily exposure to chlorpyrifos, contributing 84.7% on average. Solid food intake accounted for 13.2% of the average aggregate daily exposure. Incidental ingestion of carpet dust, dermal absorption of carpet dust, incidental ingestion of soil, and dermal absorption of soil contributed 0.06%, 0.76%, 1.18%, and 0.01%, respectively, on average to aggregate daily exposure. The percentage contributions to aggregate chlorpyrifos exposure from each pathway for each observation are shown in Figure 1. Exposure from inhalation of indoor air accounted for the majority of aggregate exposure for most observations. In several high-aggregate–exposure observations, contributions of solid food accounted for a substantial fraction of the total.

We restricted correlation analysis to those observations with nonzero measurements and between pathways that we considered *a priori*

Table 2. The numbers of indoor air, carpet dust, soil, and solid food samples and the number of observations with samples from all four media by cycle and overall.

Cycle	Indoor air	Carpet dust	Soil	Solid food	All four media
1	27	45	40	74	24
2	12	12	0	64	0
3	24	24	2	59	1
4	21	20	0	60	0
5	13	13	13	40	10
6	10	12	5	59	1
Overall	107	126	60	356	36

Table 3. Summary statistics for chlorpyrifos concentrations and average exposures from indoor air, carpet dust, soil, and solid food.

	No.	Mean	SD	Min	5%	25%	50%	75%	95%	Max
Chlorpyrifos concentration in the four media										
Indoor air (ng/m^3)	107	31.7	89.1	0	0	2.83	6.71	21.9	149	798
Dust (ng/g)	126	2.38×10^3	4.98×10^3	0	0	103	355	1.75×10^3	1.15×10^4	2.70×10^4
Dust (ng/m^2)	126	7.31×10^3	2.05×10^4	0	0	101	451	1.89×10^3	5.18×10^4	1.16×10^5
Soil (ng/g)	60	204	951	0	0	0	0	30.6	492	6.49×10^3
Food (ng/kg)	356	748	2.21×10^3	0	0	0	0	850	2.90×10^3	2.43×10^4
Average daily exposure (ng/day) through the different pathways and in aggregate										
Inhalation of indoor air	107	594	1.60×10^3	0	0	34.2	103	463	2.99×10^3	1.39×10^4
Incidental ingestion of carpet dust	126	0.103	0.357	0	0	0	0	0.0722	0.386	3.22
Dermal absorption of carpet dust	126	4.25	22.1	0	0	0	0	1.3437	15.8	239
Incidental ingestion of soil	60	4.27	27.7	0	0	0	0	0	6.81	214
Dermal absorption of soil	60	0.0394	0.256	0	0	0	0	0	6.28×10^2	1.98
Ingestion of solid food	356	285	902	0	0	0	0	328	1.24×10^3	1.02×10^4
Aggregate	36	1.39×10^3	2.77×10^3	13.5	13.8	62.3	112	1.08×10^3	9.75×10^3	1.28×10^4

Abbreviations: Max, maximum; Min, minimum.

to have plausible physical associations. Chlorpyrifos concentrations in indoor air and carpet dust were significantly correlated in rank order (n = 72, Spearman r = 0.56, p = 0.0001), whereas the linear correlation was weaker and not significant (n = 72, Pearson r = 0.17, p = 0.1247). Exposure from inhalation of indoor air was significantly correlated in rank order with exposure from incidental ingestion of carpet dust (n = 41, Spearman r = 0.44, p = 0.0038) and dermal absorption of carpet dust (n = 41, Spearman r = 0.60, p = 0.0001); the linear correlations were weaker and not significant (ingestion, n = 41, Pearson r = 0.14, p = 0.3925; absorption, n = 41, Pearson r = 0.01, p = 0.9698). The concentration in soil was not significantly correlated with the concentrations in indoor air (n = 18, Spearman r = 0.29, p = 0.2502) or in carpet dust (n = 16, Spearman r = 0.13, p = 0.6251).

We calculated reliability to evaluate temporal variability in the data sets restricted to participants who were involved in two or more sampling cycles for indoor air, carpet dust, and solid food. The intraclass correlation coefficient of reliability was 0.55 for the concentrations of chlorpyrifos in indoor air (n = 85). For the concentrations of chlorpyrifos in carpet dust (n = 99) and duplicate plates (n = 356), the intraclass correlation coefficient of reliability was 0.90 and 0.03, respectively.

Discussion

Information on the sources and magnitude of chlorpyrifos exposure is important for exposure and risk assessment of populations and individuals regarding potential health impacts of this common insecticide. In addition, the direct measurements of exposure to chlorpyrifos through indoor air, carpet dust, soil, and solid food reported in this study can be used to understand better the accuracy of pesticide safety assessments based on indirect methods or models.

Chlorpyrifos concentrations and exposures through different pathways based on those media have been measured or modeled in other studies, although few of these investigations contain the breadth of exposure media and pathways provided through the present work. The chlorpyrifos detection frequency and concentrations in our study for indoor air, carpet dust, and soil were in the same range as those from NHEXAS–Arizona (*15*) and the Minnesota Children's Pesticide Exposure Study (MNCPES) (*16*). Chlorpyrifos concentrations in settled dust and indoor air following indoor broadcast and other application methods may be 10-fold greater than the corresponding concentrations in the present study (*17–19*). Yet, our highest levels are in the range of the lowest levels observed up to 10 days after indoor application of chlorpyrifos (*18*).

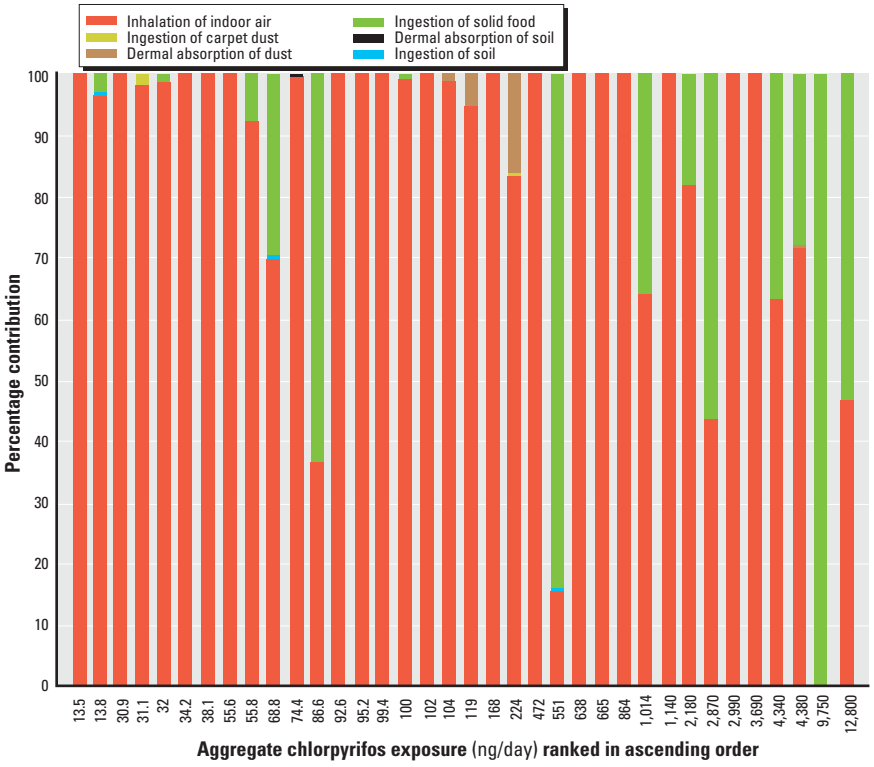

Figure 1. Pathway-specific percentage contributions for individual observations of aggregate chlorpyrifos exposure.

Scenario-based estimates of exposure to chlorpyrifos are much greater than the exposures observed in our study and sometimes produce different conclusions about the relative contributions from different exposure media. For example, Fenske et al. (*17*) concluded that dermal absorption represented approximately 68% of the aggregate exposure (0.04–0.06 mg/kg/day) to a hypothetical infant. In contrast, our results agreed with Byrne et al.'s (*18*) finding that contact with household surfaces and subsequent hand-to-mouth activity contribute little to overall chlorpyrifos exposure. Similarly, estimates of nondietary ingestion of chlorpyrifos from treated indoor and outdoor surfaces published in a modeling study were up to several orders of magnitude higher than corresponding measures in our study (*5*). Several investigations have been conducted of exposure to chlorpyrifos via solid food ingestion. Details of comparisons between those works and our study are reported elsewhere (*9*). Caution should be exercised when comparing exposure values across studies because of differences in application rates, study populations, and sampling and analysis protocols.

To evaluate aggregate daily exposure to chlorpyrifos accurately, pathways and activities that represent the greatest potential exposure should be identified correctly. Aggregate daily exposure as assessed in the present study accounted only for pathways and activities related to the residence. Exposure to chlorpyrifos from environmental media in work areas and other places is required to conduct a more comprehensive aggregate assessment. Nevertheless, the time activity data show that people in this population spent the majority of their time inside at home every day (mean = 16 hr), which suggests residential exposure is an important part of aggregate exposure. The duplicate plate methodology employed here is prone to its own types of errors. For example, 9% of the respondents indicated that at least some food was not included in the diet samples for reasons including illness, travel, not eating at home, limited food availability, and fatigue. Regarding limitations of the inhalation assessments, we measured chlorpyrifos concentrations in indoor air in one location in each household. Data are needed on the spatial distribution of indoor air chlorpyrifos levels to assess the impact of this limitation on our results, although data for other air pollutants indicate that spatial variation within homes is low in the absence of discrete emission sources (*20,21*). Similarly, we collected dust samples from a limited area of carpet in each household. Additional data are needed to evaluate the spatial variability of chlorpyrifos in settled dust indoors including carpet and hard surfaces in the

household. However, data from the MNCPES indicate that chlorpyrifos loading (nanograms per square centimeter) on carpet and smooth indoors surface may be similar (*16*); thus, we did not quantify a potentially significant pathway of dermal and incidental ingestion exposure. We did not detect chlorpyrifos residues in duplicate beverage and drinking water samples (*9,22*); thus, omitting these media from the assessment had no impact on estimates of aggregate exposure. Our ability to evaluate soil-derived exposure was limited by the small sample size for this medium (only 60 observations from three cycles). Although the available information suggests soil is a minor contributor to aggregate exposure for this population, more data are needed to assess this pathway fully. We obtained contact frequency and contact time for all pathways except ingestion from food in our study from questionnaires rather than via direct measures based on observations, videography, or even diaries (*23*). That means that our results may be influenced by participants' memories. We obtained factors used to estimate inhalation rate, transfer of dust and soil from surface to skin, and absorption of chlorpyrifos from the exposure literature (Table 1). For example, we estimated the adherence factor used in dermal absorption of soil as the average of the adherence factors associated with potentially relevant outdoor activities (*13*). Because of these limitations in knowledge, the assessment conducted for dermal and incidental ingestion exposure is highly uncertain.

A principal objective of this study was to identify the important pathways of chlorpyrifos exposure for this population. We found that inhalation of indoor air and ingestion of solid food accounted for almost all (97.9% together) exposure to chlorpyrifos on average. This result is based on only 36 observations for which we have contemporaneous chlorpyrifos concentration and exposure factor data for indoor air, carpet dust, soil, and solid food. By omitting soil pathways, 96 observations of aggregate exposure are obtained based on indoor air, carpet dust, and solid food. In that case, exposure from inhalation of indoor air still accounted for the majority (76.1%) of aggregate daily exposure to chlorpyrifos on average, followed by solid food intake at 22.8%. Incidental ingestion and dermal absorption of carpet dust contributed, on average, 0.04% and 1.0%, respectively, in this larger data set. This information indicates that our conclusions about contributions from each pathway were not unique to the 36-observation data set.

Our choice to treat nondetectable chlorpyrifos concentrations as zero rather than a nonzero value did not bias the aggregate exposure findings. For example, when we set nondetects to one-half the DL for the respective media, inhalation accounted for 72% of population exposure and diet for 26%, and each of the other pathways contributed < 1% to the total exposure.

Lack of knowledge about absorption of chlorpyrifos in the lung and gastrointestinal tract and through the skin contributes to uncertainty in the exposure estimates presented here. For example, we are not aware of empirical data on chlorpyrifos absorption following respiratory exposure. We assumed that 100% of inhaled chlorpyrifos is absorbed, following Hubal et al. (*4*) and Byrne et al. (*18*), whereas other investigators have assumed a 70% absorption efficiency for respiratory exposures (*24,25*). Human volunteers who ingested neat chlorpyrifos are estimated to have absorbed 70–90% of the administered dose (*26,27*). We assumed that 50% of ingested chlorpyrifos is absorbed in accordance with assumptions made by a team of U.S. EPA investigators (*4*) under the assumption that the food matrix inhibits absorption. The dermal absorption efficiency of chlorpyrifos is reported to be approximately 1% based on studies with human volunteers (*26,27*). Values in this range have been used in other dermal exposure and dose-modeling studies (*4,18,25*). Additional knowledge is needed about absorption of chlorpyrifos across biologic membranes. Yet, the current degree of uncertainty does not alter our findings that inhalation and dietary ingestion are the principal pathways of exposure for this study population.

The findings from repeated-measure studies have implications for tools such as epidemiology and quantitative risk assessment that are used to evaluate the potential effects of environmental contaminants on human health. In the NHEXAS-MD study, we found moderate ($R = 0.55$) within-person variability of chlorpyrifos concentration in indoor air over time, indicating that within-person and between-person variation contributed almost equally to total variance in the short-term measure of indoor air concentration. We found low temporal variability of chlorpyrifos concentration in carpet dust, indicating that the timing of dust sample collection may not be an important design consideration in the absence of a recent pesticide application event. But mean time spent inside the home and carpet contact rate varied significantly among cycles and among days for individuals (*10,28*). Dietary intake of chlorpyrifos exhibited low reliability, perhaps because of variation in short-term food consumption and in the occurrence and exposure concentration of chlorpyrifos among servings of food commodities. Thus, with regard to determining the levels of exposure for an epidemiologic study, our results indicate that a single short-term measure of chlorpyrifos exposure for an individual based on environmental monitoring and exposure factor data may not yield an accurate estimate of chronic exposure for that individual.

Conclusion

Research is needed to reduce uncertainty about exposure concentrations, factors, and models and to yield more realistic assessments of aggregate exposure to environmental contaminants (*4*). NHEXAS-MD is a pilot investigation for future national-scale, multimedia, multipollutant exposure assessment studies. The study design affords evaluation of aggregate daily chlorpyrifos exposure from realistic ordinary life in a randomly sampled population. Direct measurements of chlorpyrifos concentrations in potential contact media and time activity pattern data such as those reported here, in conjunction with data from controlled experiments and improved exposure factor information, can help to reduce uncertainty in pesticide exposure and risk assessments. The results of the present aggregate exposure study are based on measurements of chlorpyrifos in indoor air, carpet dust, soil, and solid food. The aggregate exposure rate for chlorpyrifos varied over a wide range and up to 12.8 μg/day. Inhalation of indoor air was the most important pathway of aggregate exposure. Concentrations of chlorpyrifos in indoor air and carpet dust were significantly correlated, which may have implications for aggregate exposure to this substance and other semivolatile insecticides. The NHEXAS-MD study design helps to illustrate patterns in aggregate temporal exposure to chlorpyrifos through various media. The timing of sample collection may not be important for assessment of chlorpyrifos concentration in carpet dust but could influence the results of indoor air and solid food chlorpyrifos measurements. However, variation in exposure to chlorpyrifos from those media and in aggregate should be considered with respect to temporal variability of people's activity patterns.

References and Notes

1. Goldman LR. Linking research and policy to ensure children's environmental health. Environ Health Perspect 106(suppl 3):857–862 (1998).
2. Wagner JM. Food Quality Protection Act: its impact on the pesticide industry. Qual Assur 5:279–283 (1997).
3. U.S. EPA. Draft Standard Operating Procedures (SOPs) for Residential Exposure. Washington, DC:U.S. Environmental Protection Agency, 1997.
4. Hubal EA, Sheldon LS, Zufall MJ, Burke JM, Thomas KW. The challenge of assessing children's residential exposure to pesticides. J Expo Anal Environ Epidemiol 10:638–649 (2000).
5. Zartarian VG, Özkaynak H, Burke JM, Zufall MJ, Rigas ML, Furtaw EJ Jr. A modeling framework for estimating

children's residential exposure and dose to chlorpyrifos via dermal residue contact and nondietary ingestion. Environ Health Perspect 108:505–514 (2000).
6. Calderon RL. The epidemiology of chemical contaminants of drinking water. Food Chem Toxicol 38(1):S13–S20 (2000).
7. Zahm SH, Ward MH, Blair A. Pesticides and cancer. Occup Med 12:269–289 (1997).
8. Zahm SH, Ward MH. Pesticides and childhood cancer. Environ Health Perspect 106(suppl 3):893–908 (1998).
9. MacIntosh DL, Kabiru CW, Ryan PB. Longitudinal investigation of dietary exposure to selected pesticides. Environ Health Perspect 109:145–150 (2001).
10. Echols SL, MacIntosh DL, Hammerstrom KA, Ryan PB. Temporal variability of microenvironmental time budgets in Maryland. J Expo Anal Environ Epidemiol 9:502–512 (1999).
11. Roberts J, Budd W, Ruby M, Camann D, Fortmann R, Lewis R, Wallace L, Spittler T. Human exposure to pollutants in the floor dust of homes and offices. J Expo Anal Environ Epidemiol 2:127–146 (1992).
12. Scanlon KA, MacIntosh DL, Hammerstrom KA, Ryan PB. A longitudinal investigation of solid-food based dietary exposure to selected elements. J Expo Anal Environ Epidemiol 9:485–493 (1999).
13. U.S. EPA. Exposure Factors Handbook, Vol 1, General Factors. Washington, DC:U.S. Environmental Protection Agency, 1997.
14. Fleiss JL. Reliability of measurement. In: The Design and Analysis of Clinical Experiments. New York:John Wiley & Sons, 1986;1–32.
15. Gordon SM, Callahan PJ, Nishioka MG, Brinkman MC, O'Rourke MK, Lebowitz MD, Moschandreas DJ. Residential environmental measurements in the National Human Exposure Assessment Survey (NHEXAS) pilot study in Arizona: preliminary results for pesticides and VOCs. J Expo Anal Environ Epidemiol 9:456–470 (1999).
16. Lioy PJ, Edwards RD, Freeman N, Gurunathan S, Pellizzari E, Adgate JL, Quackenboss J, Sexton K. House dust levels of selected insecticides and a herbicide measured by the EL and LWW samplers and comparisons to hand rinses and urine metabolites. J Expo Anal Environ Epidemiol 10:327–340 (2000).
17. Fenske RA, Black KG, Elkner KP, Lee CL, Methner MM, Soto R. Potential exposure and health risks of infants following indoor residential pesticide applications. Am J Public Health 80:689–693 (1990).
18. Byrne SL, Shurdut BA, Saunders DG. Potential chlorpyrifos exposure to residents following standard crack and crevice treatment. Environ Health Perspect 106:725–731 (1998).
19. Lu C, Fenske R. Air and surface chlorpyrifos residues following residential broadcast and aerosol pesticide applications. Environ Sci Technol 32:1386–1390 (1998).
20. Ju C, Spengler J. Room-to-room variations in concentrations of respirable particles in residences. Environ Sci Technol 15:592–596 (1981).
21. Schneider P, Lorinci G, Gebefugi IL, Heinrich J, Kettrup A, Wichmann HE. Vertical and horizontal variability of volatile organic compounds in homes in eastern Germany. J Expo Anal Environ Epidemiol 9:282–292 (1999).
22. MacIntosh D, Hammerstrom K, Ryan P. Longitudinal exposure to selected pesticides in drinking water. Hum Ecol Risk Assess 5:575–588 (1999).
23. Zartarian VG, Ott WR, Duan N. A quantitative definition of exposure and related concepts. J Expo Anal Environ Epidemiol 7:411–437 (1997).
24. Buck RJ, Ozkaynak H, Xue J, Zartarian VG, Hammerstrom K. Modeled estimates of chlorpyrifos exposure and dose for the Minnesota and Arizona NHEXAS populations. J Expo Anal Environ Epidemiol 11:253–268 (2001).
25. Rigas ML, Okino MS, Quackenboss JJ. Use of a pharmacokinetic model to assess chlorpyrifos exposure and dose in children, based on urinary biomarker measurements. Toxicol Sci 61:374–381 (2001).
26. Griffin P, Mason H, Heywood K, Cocker J. Oral and dermal absorption of chlorpyrifos: a human volunteer study. Occup Environ Med 56:10–13 (1999).
27. Nolan RJ, Rick DL, Freshour NL, Saunders JH. Chlorpyrifos: pharmacokinetics in human volunteers. Toxicol Appl Pharmacol 73:8–15 (1984).
28. Echols SL, MacIntosh DL, Ryan PB. Temporal patterns of activities potentially related to pesticide exposure. J Expo Anal Environ Epidemiol 11(5):389–397 (2001).
29. Phillips LJ, Fares RJ, Schweer LG. Distributions of total skin surface area to body weight ratios for use in dermal exposure assessments. J Expo Anal Environ Epidemiol 3:331–338 (1993).
30. CARB. Measurement of Breathing Rate and Volume in Routinely Performed Daily Activities, Final Report, Contract No. A033-205. Sacramento, CA:California Environmental Protection Agency, Air Resources Board, 1993.
31. U.S. EPA. Assessment of Time-Motion Videoanalysis for the Acquisition of Biomechanics Data in the Calculation of Exposure to Children. EPA/600/X-98/006. Washington, DC:U.S. Environmental Protection Agency, 1998.